Design of a High Temperature Radiator for the Variable Specific Impulse Magnetoplasma Rocket

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The Variable Specific Impulse Magnetoplasma Rocket (VASIMR), currently under development by Ad Astra Rocket Company (Webster, TX), is a unique propulsion system that could change the way space propulsion is performed. VASIMR's efficiency, when compared to that of a conventional chemical rocket, reduces the propellant needed for exploration missions by a factor of 10. Currently plans include flight tests of a 200 kW VASIMR system, titled VF-200, on the International Space Station (ISS). The VF-200 will consist of two 100 kW thruster units packaged together in one engine bus. Each thruster core generates 27 kW of waste heat during its 15 minute firing time. The rocket core will be maintained between 283 and 573 K by a pumped thermal control loop. The design of a high temperature radiator is a unique challenge for the vehicle design. This paper will discuss the path taken to develop a steady state and transient-based radiator design. The paper will describe the radiator design option selected for the VASIMR thermal control system for use on ISS, and how the system relates to future exploration vehicles.

Nomenclature

ATCS = Active Thermal Control System
ISS = International Space Station
K = Kelvin
kPa = kilopascal
kW = kilowatt
psid = differential pounds per square inch
VASIMR = Variable Specific Impulse Magnetoplasma Rocket

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I. Introduction

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is an advanced electric propulsion technology currently under development by Ad Astra Rocket Company. This technology has the potential to greatly improve the propulsion efficiency of future spacecraft over what could be achieved with chemical rocket engines. Improved propulsion efficiency is a virtual necessity to enable a human mission to Mars.

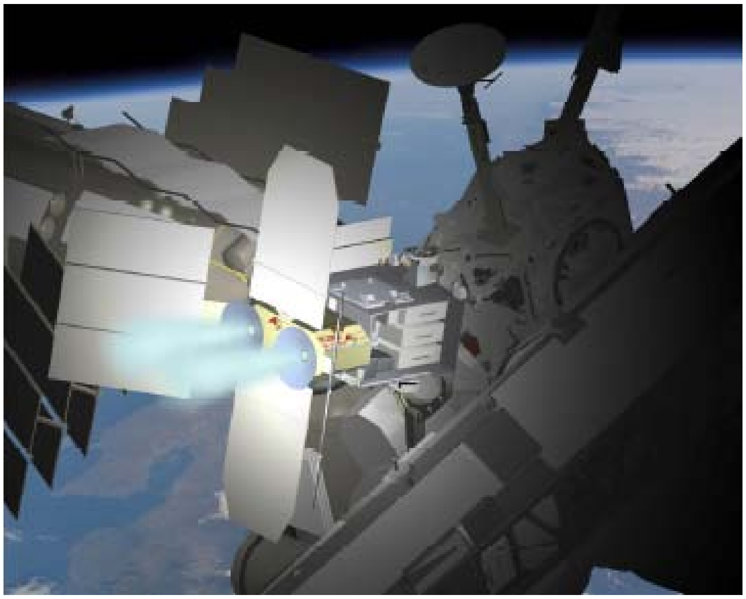

Figure 1. VF-200 engine attached to the International Space Station. (Artist's Conception.)

The VF-200 engine is planned as a demonstration of VASIMR technology on the International Space Station (ISS). The VF-200 will consist of two 100 kW thruster units packaged together in one engine bus. The VF-200 will be sized as if it were on a free-flying spacecraft with a dedicated power feed of 200 kW. In this application, the VASIMR core cooling requirement is 27 kW for each of two cores. The core cooling is accomplished using an internal cooling jacket that is maintained below 573 K.

The VF-200 will be located on ISS, as shown in Fig. 1. Although the ISS total power capability is approximately 75 kW, the power available at the truss location chosen for the VF-200 is limited to approximately 5 kW. Therefore, the ISS version of the VF-200 will include batteries that can be charged over the course of several days, allowing the rocket to fire at full power for periods of 15 minutes every 72 hours.

Because the rocket firings are intermittent and the VF-200 has a great deal of inherent thermal mass, the heat rejection system does not need to be sized for the full 54 kW. Instead, it can be sized for an "average" heat load. However, because the VF-200 rocket might serve as the basis for a free-flying spacecraft, the Active Thermal Control System (ATCS) will be sized for acquisition and transport of the full 54 kW of heat load.

The present work describes the component and system level trades that were performed in the design of the VF-200 ATCS. The processes of working fluid selection, basic ATCS design, and radiator sizing and design are presented.

II. Detailed Active Thermal Control System Design

The VF-200 core must be maintained above 283 K for startup and is limited to 573 K during operation. While the wide allowable temperature range allows use of a simplified ATCS, the extreme high temperature limit presents a significant design challenge. The ATCS development process and the final design are detailed next.

A. Heat Acquisition and Transport

The ATCS is simplified by taking advantage of the wide range of allowable core temperatures. Because the core must be maintained between 283 and 573 K, it was decided to use a simple pumped loop for each thruster without a radiator bypass temperature control. Eliminating the normally included radiator bypass setpoint control dramatically simplified the system and the system control. A notional schematic of the ATCS is shown in Fig. 2. The figure shows one of two loops, each of which cools a single core.

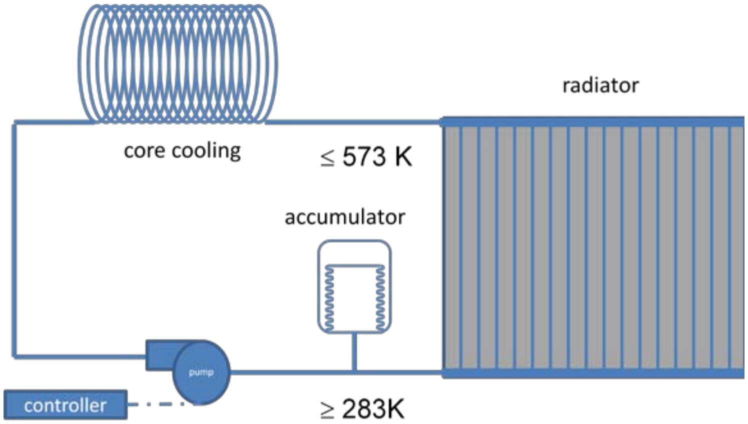

Figure 2. Active Thermal Control System notional schematic.

The working fluid selection was based on several criteria:

- Operating range between ambient temperature and 573 K.
- A viscosity compatible with a hydrodynamic bearing pump.
- A low freezing point for design margin.

The working temperature limits led us to the Dowtherm family of heat transfer fluids. We considered several formulations that met the temperature and viscosity requirements. Dowtherm J meets the VF-200 temperature limits with margin and has a favorable viscosity curve. The operating temperature range of Downtherm J is from 193 to 588 K.[1]

Ad Astra Rocket Company set the Dowtherm J flow rate to the core at 0.41 kg/s (3254 lb/hr) to provide sufficient cooling to the core heat exchanger. This flow rate is compatible with the full steady-state heat load of 27 kW. The full flow passes through the radiator at all times, owing to the simplified ATCS design.

B. Transient vs. Steady-State Radiator Design

Because the VF-200 is limited to a 15 minute operating period every three days the radiator was sized based on transient heat rejection requirements. The core heat load is 27 kW during VF-200 operation. The ATCS heat load is the expected pump power of 300 W during quiescent periods. The radiator was designed to maintain the pump inlet temperature below 573 K during VF-200 operation and above 283 K during quiescent periods.

Before designing the transient radiator, a steady-state radiator was sized to provide a point of comparison. The steady state radiator was sized for three different radiator coatings: silver Teflon, white paint, and black paint. Table 1 contains the emissivity and absorptivity for each coating[2] and their corresponding sink temperatures. The sink temperatures represent orbit averaged hot case sink temperatures at the VF-200 location onISS. Due to the high VF-200 radiator temperature, the orbit average sink temperature was an acceptable first order approximation. The table also includes the one-sided radiator area required for an isothermal 573 K radiator with a 95% fin efficiency to reject 27 kW.

Table 1. Emissivity, Absorptivity, Radiator Sink Temperatures, and Sizing

Coatings	Emissivity	Absorptivity	Sink Temperature (K)	27 kW 573 K Radiator Area (m^2)
Silver Teflon	0.88	0.09	270	8.1
White Paint	0.9	0.24	294	8.2
Black Paint	0.96	0.88	367	10.0

The table shows that large, but not unreasonable, radiator areas are required to reject 27 kW. Radiators of this size would need to be mechanized to allow deployment, thereby adding mass and volume to the flight experiment. A transient design for the radiator was pursued to save mass and reduce complexity.

The general concept of a transient radiator was to use thermal mass to damp the short-lived 27-kW heat load and to size the radiator for the average heat rejection of 393 W over the three day operating cycle. The coolant would be maintained within the operating limits of 283 to 573 K.

A simple Thermal Desktop model was built to explore the response of a transient VF-200 radiator. The following assumptions were made for the model:

- Constant 0.41 kg/s of Dowtherm J coolant flow
- Radiator fin efficiency of 95%
- A temperature difference of 2.5 K between the fluid and the radiator fin root at maximum heat load

The following estimates were developed with Ad Astra Rocket Company for ATCS loop parameters for the model:

- 140 kg of stainless steel for the core heat exchanger and ATCS tubing
- Radiator mass of 5.8 kg/m^2
- 20 liters of Dowtherm J in the fluid loop

The Thermal Desktop model was used to predict the ATCS performance over a range of radiator areas. The analysis showed that additional thermal mass was required to maintain the system within the prescribed temperature limits. Given a 283 K initial temperature, an additional thermal mass of 18 kg of aluminum was required to prevent the peak temperature from exceeding 573 K. With this additional mass, the required radiator area of 1.60 m^2 was calculated. The radiator temperature prediction is shown in Fig. 3. The analysis was begun with 9 days of operating cycles, followed by the 3 days of cycles that are shown in the figure.

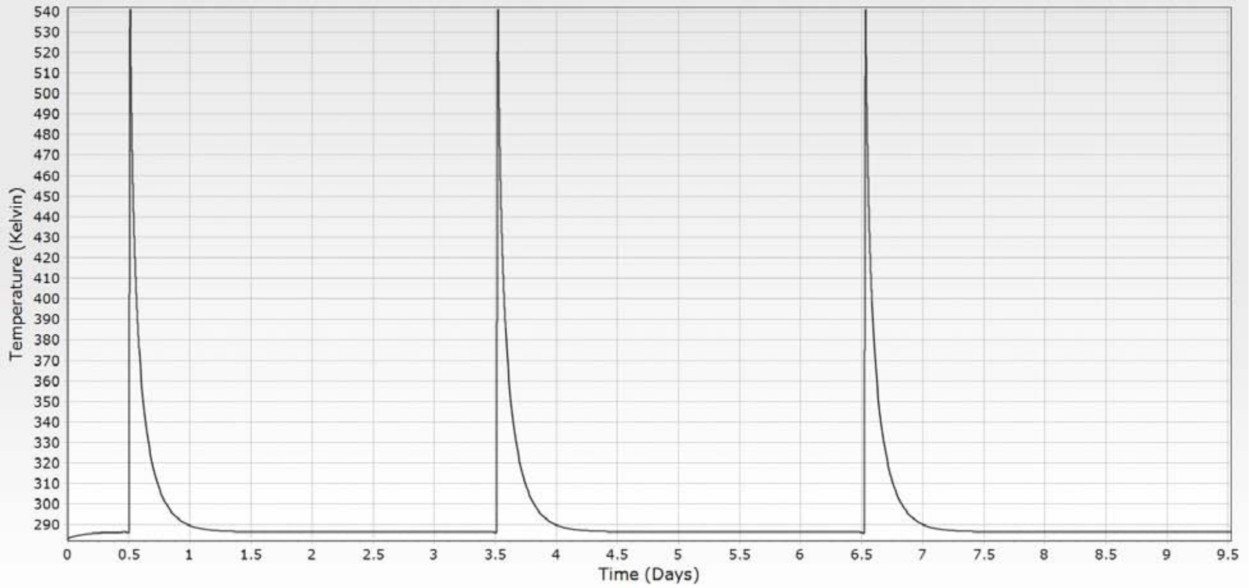

Figure 3. Radiator surface temperature for transient radiator design.

Given the small required radiator size, the team decided to proceed with a transient body mounted radiator design solution for the VF-200 active thermal control system.

C. Fin Efficiency Optimization

The thermal control loop was designed to maintain temperatures below 573 K during operation of the VF-200 rocket. The high upper temperature limit dictated that a non-traditional material be used for the radiator. Grade 3 titanium was selected owing to its strength at high temperatures. Even though the thermal conductivity of Grade 3 titanium is 1/9th that of aluminum, it is still significantly higher than that of 316L stainless steel. The low thermal conductivity of Grade 3 titanium requires closely spaced coolant tubes on the radiator. To assess the tube spacing for the radiator, the fin efficiency was calculated for a various set of radiator facesheet thicknesses, tube spacings, and fin root temperatures.

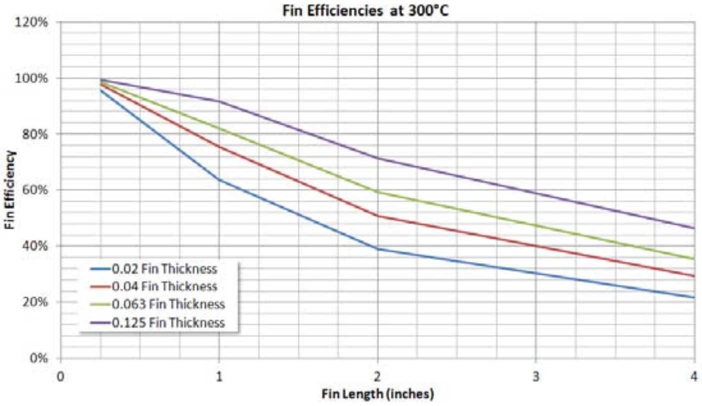

Figure 4. Radiator fin efficiency for various fin thicknesses and fin lengths at 573 K.

The analysis was performed for:

- radiator facesheet thicknesses of 0.51, 1.02, 1.59, and 3.18 mm
- fin pitches of 6.35, 25.4, 50.8, and 100.6 mm
- fin root temperatures ranging from 273 to 573 K

A simple Thermal Desktop model was made to generate temperature distribution for each radiator facesheet thickness and tube spacing. The resulting temperatures profiles were used to calculate the fin efficiency. The results for a fin root temperature of 573 K are plotted in Fig. 4. The irregularities in the curves are caused by the coarseness of the fin nodalization.

A target fin efficiency of 80% was selected for the transient radiator design since that percentage coincides with the knee on the curves of Fig. 4. The model was rerun to obtain the fin pitch for each fin thickness that corresponds to an 80% fin efficiency. Table 2 provides a summary of the results.

Table 2. Fin Pitch and Thickness for 80% Fin Efficiency at 573 K

Fin Thickness (mm)	Fin Pitch (mm)
0.51	15.7
1.02	21.8
1.59	27.2
3.18	39.6

D. Radiator Design

The chosen fin efficiency of 0.80 and the selection of Grade 3 titanium provided the basis for the radiator design. Given the titanium thermophysical properties, the fin root temperature, the sink temperature, and the environment temperature, the fin pitch was calculated for standard facesheet thickness of 1.01, 1.60, and 3.18 mm. The radiator size was increased to 1.90 m^2 to account for the change in fin efficiency from 95% in the sizing calculations to the 80% used in the design. The radiator for each loop was sized at 1.5 by 1.27 m, based on the radiator length limit imposed by the VF-200 spacecraft. The remainder of the radiator design process consisted of balancing the number of passes, the tube diameters, and manifold diameters to yield the radiator with the best thermal performance that met the preliminary pressure drop design requirement of 0.02 kPa (0.0029 psid). We selected flow the long way on the radiator so that the heavier manifolds were of the shortest length. The optimized parameters for each of the three facesheet thicknesses are shown in Table 3.

Table 3 – Radiator Parameters

facesheet thickness (mm)	1.01	1.60	3.18
# passes	2	2	4
tube OD (mm)	6.35	6.35	7.95
tube ID (mm)	4.57	4.57	6.17
tube pitch (mm)	21.8	27.2	39.6
wet mass (kg)	17.0	20.7	32.2
manifold OD (mm)	25.4	25.4	25.4
manifold ID (mm)	23.6	23.6	23.6

The film temperature drop (from the Dowtherm J to the tube wall) ranged from 2.5 to 3.5 K, which is well within a reasonable range. Not surprisingly, the radiator mass correlated with the facesheet thickness. We selected the 1.60mm thick radiator as it gave a good compromise between mass, stiffness, and ease of fabrication. The radiator is designed to be monolithic with the flow tubes and manifolds welded to the facesheet, as shown in Fig. 4 and Fig. 5.

III. Conclusion

An active thermal control system has been designed for the VF-200 Variable Specific Impulse Magnetoplasma Rocket (VASIMR) that will be demonstrated on the International Space Station. The ATCS uses full prototypic core cooling flow to acquire the waste heat. It uses a minimally sized radiator to reject the waste heat generated by the 15 minute rocket firings that occur every 3 days.

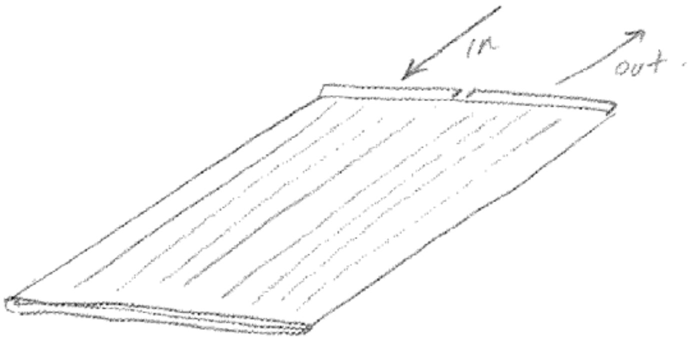

Figure 4. Active Thermal Control System radiator (1 of 2).

Acknowledgments

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[1] Dowtherm J Heat Transfer Fluid, http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0040/0901b80380040b97.pdf?filepath=heattrans/pdfs/noreg/176-01465.pdf&fromPage=GetDoc, accessed February 29, 2012.

[2] TBD Optics Reference.